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LAMONT GEOLOGICAL OBSERVATORY

PALISADES, NEW YORK

DYE DIFFUSION EXPERIMENTS IN THE NEW YORK BIGHT

Report prepared by: M. Costin
P. Davis
R. Gerard
B. Katz

Technical Report No. CU-2-63 to the Atomic Energy Commission
Contract AT(30-1)2663

February, 1963

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ABSTRACT

A series of seven surface experiments involving the use of Rhodamine B dye as an artificial tracer is described. The experiments were made during the fall of 1961 near Ambrose Lightship and at a position fifteen miles south southeast of Ambrose near the center of the Hudson Channel. The fluorometer used in the field was calibrated to reveal concentrations of 1×10^{-11}.

The paper describes general experimental procedures, including dye sampling, navigation, aerial photography and data analysis. For the experiments of October 17 and October 31, 1961, plots of the movement of their respective mass centers, along with contours of constant dye concentration and aerial photographs at various hours after the surface dye introduction, are shown. Graphs of concentration vs. radius and the decrease of concentration with time are also shown and compared with theory.

The average diffusion velocity for these experiments is observed to be approximately 1 cm/sec.

INTRODUCTION:

Multiple ship synoptic surveys (e.g ., OPERATION CABOT, 1950 in the Gulf Stream) have recently shown that surface ocean currents are complex structures containing eddies of various scales, filaments and jets rather than steady streams. As a consequence of this turbulence in the surface waters, dissolved materials are dispersed horizontally at a rate perhaps a million times greater than by molecular diffusion, the rate depending on wind stress, current shear, density gradients, direction of dispersion and the dimensions of the area considered. Artificial tracer experiments have begun to help in our calculation of diffusion velocities where classical oceanographic measurements have been inconclusive. The first large-scale experiments of this nature followed the Bikini tests in 1946 (Folsum & Vine, 1957). More recently Pritchard and his co-workers (Pritchard and Carpenter, 1960) developed a tracer technique using harmless organic dyes which, for the first time, provide a method comparable in sensitivity for low concentrations to the radioactive tracer techniques. The present report describes several experiments and their results using introductions of Rhodamine B dye in the surface waters in the New York Bight during the summer of 1961 in the areas indicated in Figure 1.

The hydrography and circulation of the New York Bight have been discussed for the various seasons of the year by:

Bigelow & Sears, 1935
Powers & Ayers, 1951
Ketchum, Redfield & Ayers, 1951
Ketchum, Yentsch, Corwin & Owen, 1958
Redfield & Walford, 1951

Hydrographic studies have used the low salinity effluent from the Hudson-Raritan River estuary as a tracer to show mixing and residence times, and the circulation pattern at the mouth of the estuary. In the winter, river effluent and diluted sea water are confined to a narrow band along the New Jersey coast. There is no temperature gradient, and the water is homogeneous vertically. In the mid-summer the thermocline is well established at about ten meters, and the river effluent is distributed widely over the surface. The stability of either of these patterns depends somewhat on river flow. If the flow is fairly great, the distribution patterns are well defined. If the flow is small, or if storms cross the area, the pattern can be broken up into large ill-defined eddies. Non-tidal current measurements at the surface indicate velocities of about 9.5 centimeters per second generally throughout the area. The average movement of fresh water seaward is three miles per day. Considering the area extending outward about 25 miles from the shores, it is estimated that six to ten days are required for the replacement of all this water. The average yearly flow is such that more than two years would be required for river flow to replace the entire volume. Since it is shown that only six to ten days' contribution of the river was present at any time, it is evident that oceanic circulation in the area is many times that of the river contribution. In the summer the circulation pattern is characterized by a weak southerly current along the New Jersey shore.

FIELD METHODS:

The purpose of the experiments during 1961 was to develop techniques aboard the Research Vessel JOSEPH GOLDBERGER for a dye sampling system to be

used in the surface and at moderate depths to study diffusion and mixing in typical coastal and shelf waters. The ship was outfitted to carry out the placement of dye at surface and subsurface depths and to sample the resulting dye patch so that information could be gathered concerning the changing dimensions and concentrations until extinction. For these purposes the following systems for dye sampling and navigation were set up.

DYE SAMPLING METHODS:

In order to sample continuously the dye concentration in the surface waters, two methods were employed: a submersible well pump was towed from the stern of the ship using about 50 feet of hose to connect it to the continuous flow-through cuvet of a fluorometer. With this method, continuous sampling of the surface water could be made at a speed of up to eight knots. A later method was used consisting of a positive displacement rotary pump mounted on the deck having a weighted inlet hose to bring surface water to the fluorometer.

Tests were also made of a submersible pump fitted to a depressing body which could be towed at depths of about 50 feet and speeds of 8 knots. While the tow tests were successfully accomplished, breaks in the electrical conductor prevented the use of the pump at subsurface depths.

The sample was pumped through a clear polyethylene hose to a fluorometer in the ship's laboratory at a constant flow rate of 2.5 gallons per minute. The fluorometer was a standard Turner model III, modified with a continuous-flow cuvet. This instrument is designed as an optical bridge which balances the fluorescent emission of the sample and the light from a calibrated rear light path. The photomultiplier controls a servo-motor which turns a light cam until equal amounts of light are received from the

sample and from the rear light path. The servo-motor turns a potentiometer, the output of which is connected to a chart recorder for continuous recording purposes. The dye which was used throughout these experiments was Rhodamine B obtained from E. I. Du Pont. The dye was obtained in 40% acetic acid solution and then adjusted with methanol to a density of 1.03. The optical characteristics of Rhodamine dye are such that peak fluorescence is attained under an excitation light of 550 mμ. Two filters, a Corning 1-60 didymium glass and a Kodak Wratten 58, were used to pass selectively the green line of mercury (546 mμ) of the light source to excite the sample. The maximum fluorescence of Rhodamine B occurs at 575 mμ. A sharp cut filter (Kodak Wratten 23) passing light above 570 mμ was used to pass the sample fluorescence to the photomultiplier. The fluorometer was calibrated using a series of reference concentrations of Rhodamine B in distilled water. Four scales of sensitivity are provided in the fluorometer through a selection of four apertures at the light source. In our experiments the following relation of dye concentration to fluorometer scale applies:

Fluorometer Scale	Max. Rhodamine B Range in PPB
1 X	6 - 120
3 X	.5 - 44
10 X	.6 - 17
30 X	0.01 - 3.5

NAVIGATION METHODS:

Accurate navigation must accompany the dye measurements so that precise plotting of the areal distribution of a dye patch may be accomplished. In order to afford the required navigational accuracy, a Decca 303 radar with

a variable range marker was installed aboard the research vessel. During the crossings of a dye patch, while measurements of the dye concentration were being made, the ship's position was fixed relative to an anchored radar reflector at three minute intervals.

EXPERIMENTAL PROCEDURES:

Seven experiments were successfully performed during the period from September to November, 1961. The following procedures were used generally throughout all of these experiments.

Prior to placement of dye in the water, a radar reflector spar buoy was anchored at some fixed point, generally a few miles in the direction of expected flow from the planned point of dye introduction. On some occasions lightships or significant shore points in the area were also used as fixed radar targets.

Rhodamine B dye in solution was then introduced by pumping into the surface water. Following the introduction of the dye, the ship would remain out of the dye for about four hours to prevent contamination of the intake system with concentrated dye and to avoid disturbing the patch during the initial diffusion. During this time weather readings and bathythermograms were taken. After this period crossings of the patch would be carried on whenever possible until the dye readings had merged with the fluorescent background readings (about 0.1 ppb). A typical set of crossings is superimposed on the contours of Figure 11. The record of one of these crossings is shown in Figure 11A.

AERIAL PHOTOGRAPHS:

During these experiments a useful technique was developed using aerial photographic coverage to complement the survey made by the surface vessel. In this work using Rhodamine B dye, photographs were made at about fifteen minute intervals at altitudes between 1000 and 5000 feet. Fast Polaroid (3000 speed) and Royal X Pan film (1250 speed) were used with a combination of filters depending on light conditions. Under dull conditions best results were obtained using a Polaroid filter combined with a 23A Kodak Wratten filter (blocking frequencies below 570 millimicrons and passing about thirty per cent of the fluorescent maximum of the dye at 575 millimicrons). Under bright conditions a Polaroid filter was used with a 73 Wratten filter (passing frequencies between 560 and 610 millimicrons). The photographs were used later together with shipboard data to plot areal distribution of the dye and were of particular value in determining the shape of the dye contours.

DATA ANALYSIS:

The initial aim in processing the data obtained from a point source surface dye experiment is to construct contours of equal dye concentration which represent the total distribution at suitable instants of time from introduction to the disappearance of the dye. This is done by dividing the data into time intervals which are long enough to reveal an adequate picture of the whole patch and yet short enough with respect to the diffusion rate to be considered as one instant. The next step, using a mechanical integrator, is to determine the area enclosed within each contour from which the equivalent radius, r, can be computed. In these

experiments the center of mass for each contour set has been determined from measurements of mass center for the individual contours. The center of mass has been plotted in order to show the over-all movement of the dye throughout each experiment. This point was chosen rather than the center of maximum concentration since the latter is not always measured and may, in fact, be separated into several distinct patches.

EXPERIMENT OF OCTOBER 17, 1961:

On this date one 30 gallon barrel of solution containing 3.39 x 10^4 grams of Rhodamine B was introduced at the surface near Ambrose Lightship. The location of this experiment is shown in area A, Figure 1. Figure 2, plotted on a larger scale, shows the location of the center of mass plotted for each numbered contour set during a ten-hour period. The arrows indicate the mean tidal current at the time of the various contour sets. If we compare the trajectory of the dye patch with the tidal current chart for the location of Ambrose Lightship (Tidal Current Charts, N. Y. Harbor, 1956), a close correspondence is observed both in direction and velocity. It indicates clearly that the dye movement was dominated by the tidal movement in the presence of steady, light westerly winds. Drift bottle studies of this region (Powers & Ayers, 1951) indicate the presence of a right gyral to the north and east of Ambrose. The dye's movement suggests that the rotation of the tide might lead to such an averaged circulation for the bottles. The excursion of the flood (positions 0, 1, 2 in Figure 2) is observed to be considerably less than that of the ebb (positions 3 to 6) in agreement with the tidal chart. The complex shape of the patch indicated in dye contour #1 (Figure 3), two hours after the dye dump, is

FIGURE 1.

Locations (A and B) of dye dumps in New York Bight

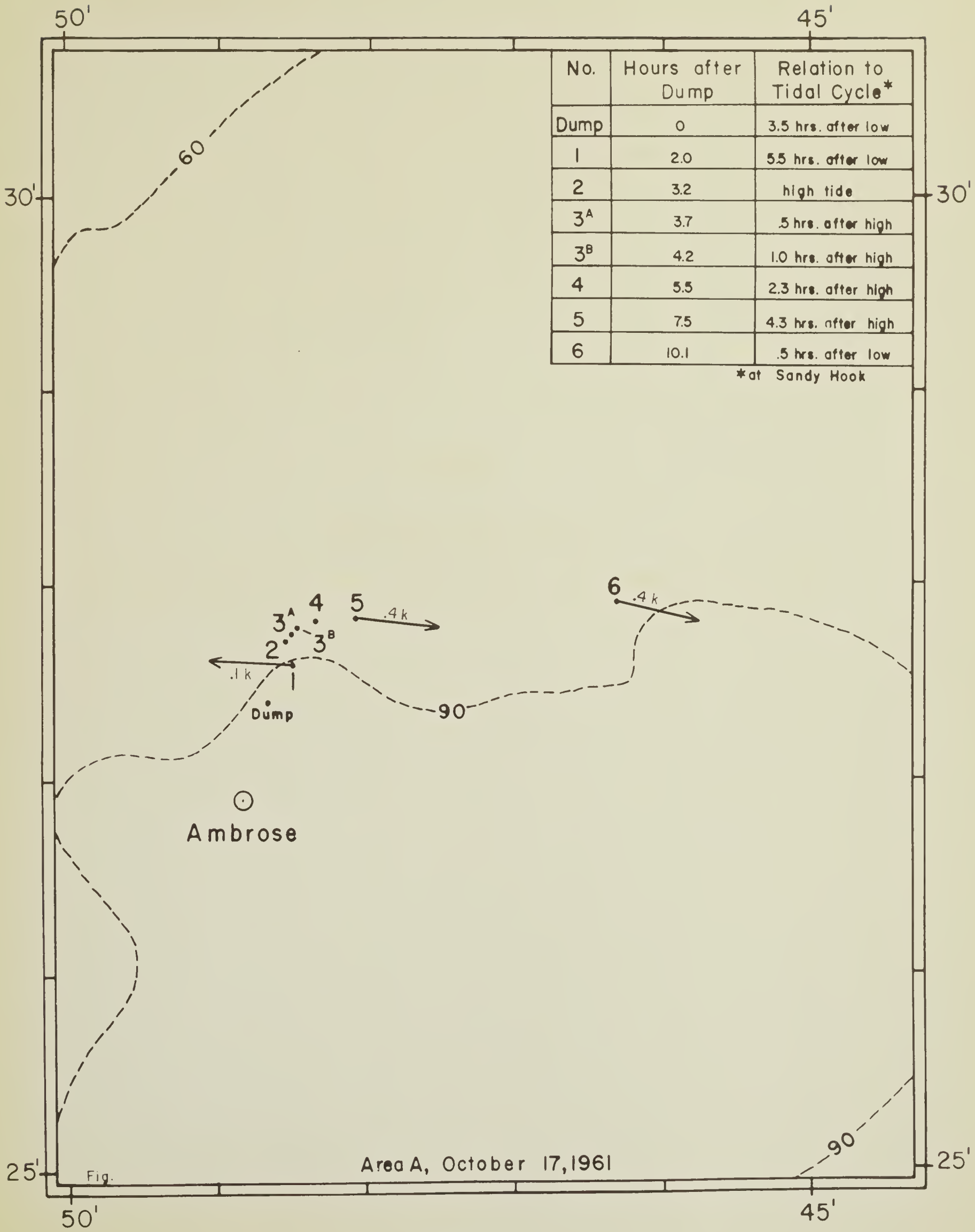

74°
50'
40'
40° 30'
20'
10'
A
B
Ambrose
Sandy Hook
Atlantic Highlands
Long Branch
Asbury Park
30
60
90
120
9/8
10/31
10/19
Radar
Buoy
10/30
Fig.

FIGURE 1

FIGURE 2.

Area A, New York Bight,

showing movement of mass center of dye patch of October 17, 1961



No.	Hours after Dump	Relation to Tidal Cycle*
Dump	0	3.5 hrs. after low
1	2.0	5.5 hrs. after low
2	3.2	high tide
3A	3.7	.5 hrs. after high
3B	4.2	1.0 hrs. after high
4	5.5	2.3 hrs. after high
5	7.5	4.3 hrs. after high
6	10.1	.5 hrs. after low

*at Sandy Hook

Fig. Area A, October 17, 1961

FIGURE 2

FIGURE 3.

Dye contour #1, October 17, 1961

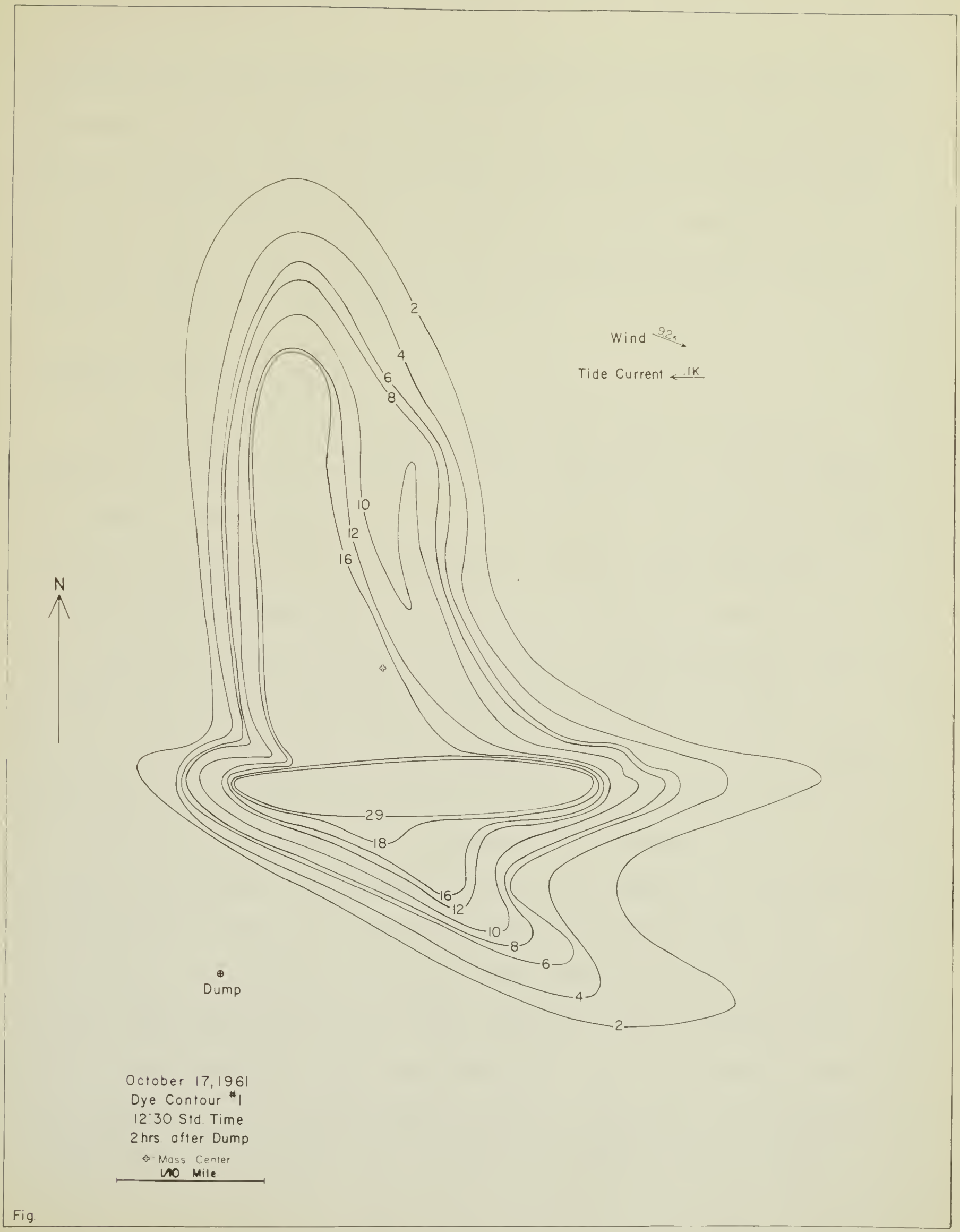

Wind 9.2 K
Tide Current .1K
N
2
4
6
8
10
12
16
29
18
16
12
10
8
6
4
2
Dump
October 17, 1961
Dye Contour #1
12:30 Std. Time
2 hrs. after Dump
Mass Center
1/10 Mile

Fig.

FIGURE 3

based upon four ship's crossings and was constructed with the help of aerial photographs such as that represented by Figure 4, taken 1.25 hours after the initial dye dump. It can be observed from the photograph that the northern portion of the patch has taken on a linear pattern that corresponds to the axis of the wave troughs. Figures 5 and 6 show dye contours for this same patch at 7.5 and 10.1 hours after the dye dump.

EXPERIMENT OCTOBER 31, 1961:

On this date four 30 gallon drums of dye solution, each containing 3.61×10^4 grams of Rhodamine B, were introduced at the sea surface in a position about twelve miles east of Asbury Park, New Jersey, indicated in area B in Figure 1. In this experiment the four barrels were pumped separately within twenty minutes at four points roughly 100 meters apart in a rectangular pattern. Figure 7 is an oblique aerial photograph taken at 1500 feet just after the fourth barrel was introduced. The ship can be seen at the northern edge of the fourth patch lying hove-to and roughly parallel to the troughs of the sea (E-W) which at this time were nearly at right angles to the wind. Two filaments of dye in this same patch can be seen streaming east northeastward. These were caused by two empty dye barrels floating high in the water and moving under the influence of a westerly wind. A series of photographs taken during the first five hours of this patch show that the dye becomes elongated roughly parallel to the swell. This elongation in the early phase of the patch is a feature common throughout most of our experiments thus far performed. The photograph in Figure 8 taken 1.5 hours after the dye dump illustrates the striated

FIGURE 4.

Aerial photograph showing surface dye patch,

October 17, 1961, 1.25 hours after dump.



FIGURE 4

FIGURE 5.

Dye contour #5, October 17, 1961

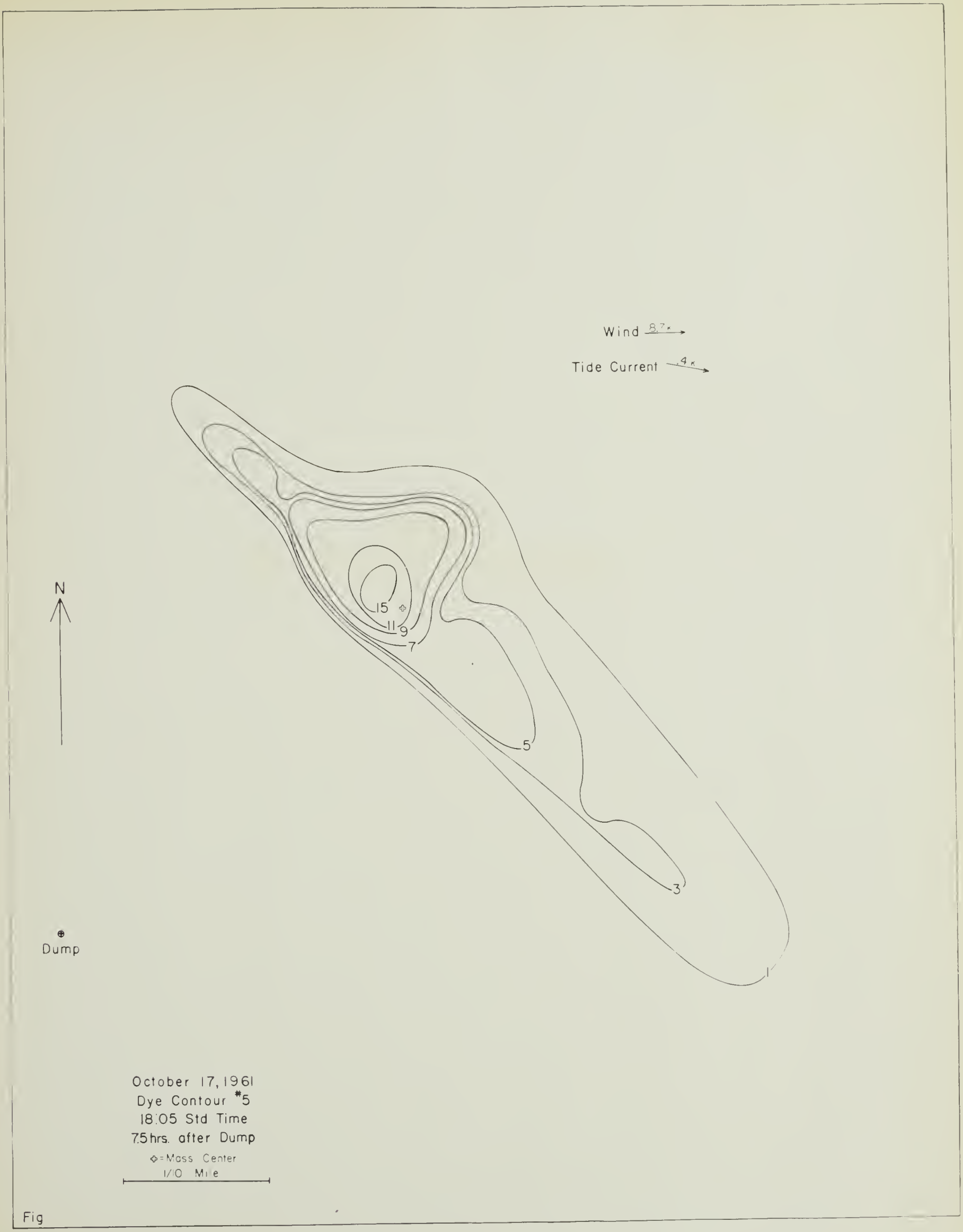
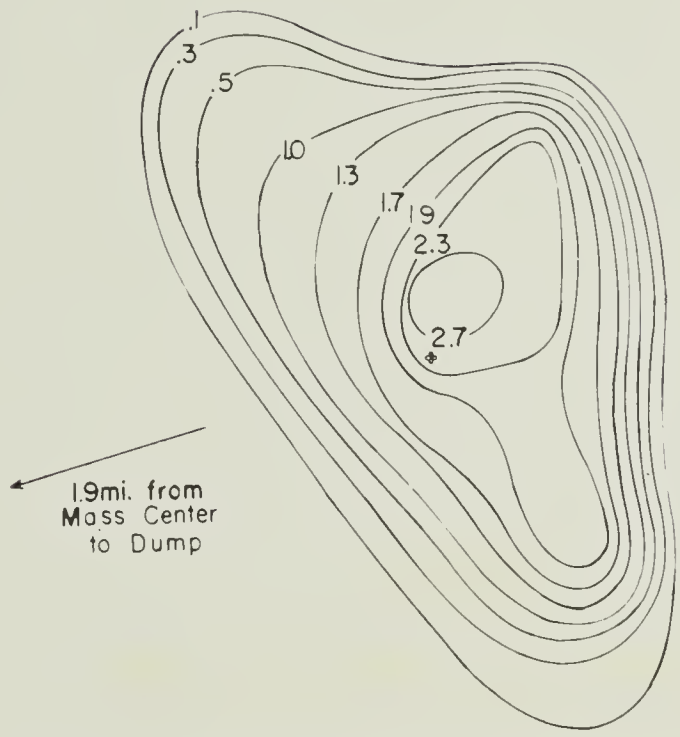

Wind 8.7 k
Tide Current .4 k
N
15
11
9
7
5
3
1
Dump
October 17, 1961
Dye Contour #5
18:05 Std Time
7.5 hrs. after Dump
⊕ = Mass Center
1/10 Mile

FIGURE 5

FIGURE 6.

Dye contour #6, October 17, 1961.



Wind 10k

Tide Current .4k

1.9mi. from Mass Center to Dump

N



October 17, 1961
Dye Contour *6
20:40 Std. Time
10.1 hrs. after Dump
◆= Mass Center
1/10 Mile

Fig

FIGURE 6

FIGURE 7.

Aerial photograph showing surface dye patch,

October 31, 1961 during dumping operations



FIGURE 7

FIGURE 8.

Aerial photograph showing surface dye patch,

October 31, 1961, 1.5 hours after dump.



FIGURE 8

appearance (left of photograph) characteristic of the initial stages. This pattern, resembling altocumulus clouds, is the result of wave action by which dye is carried to a deeper level while retaining the alignment of the swell. The trailing portion of the patch lies below the surface as indicated in Figure 9, which shows the Research Vessel JOSEPH GOLDBERGER, with a draft of 9½ feet, moving through this portion of a patch and stirring dye up from a subsurface level. The denser portion of the dye extending to the surface in Figure 9 (right of photograph) is moving somewhat to the right of the westerly wind. This and subsequent photographs show a pronounced curvature of the trailing portion of the dye. It would appear from this and other experiments that the curved trail pattern is common in the early stages of dye patches where winds are moderate and no pronounced currents prevail. Figure 10 shows the plotted position of the center of mass of this patch at intervals during twenty-five hours following the dye introduction. The arrows indicate the mean tidal current at the time of the various contour sets. Reasonably complete contours were constructed for each of these positions as demonstrated in Figures 11, 12 and 13. During the first twelve hours relatively little movement of the patch occurred. However, during the following twelve-hour period the patch moved northward about two miles to position 5, possibly under the influence of a northward moving current which has been observed in this area outside the lower salinity coastal water during the summer season (Powers & Ayers, 1951).

ADDITIONAL EXPERIMENTS:

In addition to the experiments of the 17th and 31st of October,

FIGURE 9.

Aerial photograph showing surface dye patch,

October 19, 1961, curvature to the right of the wind.

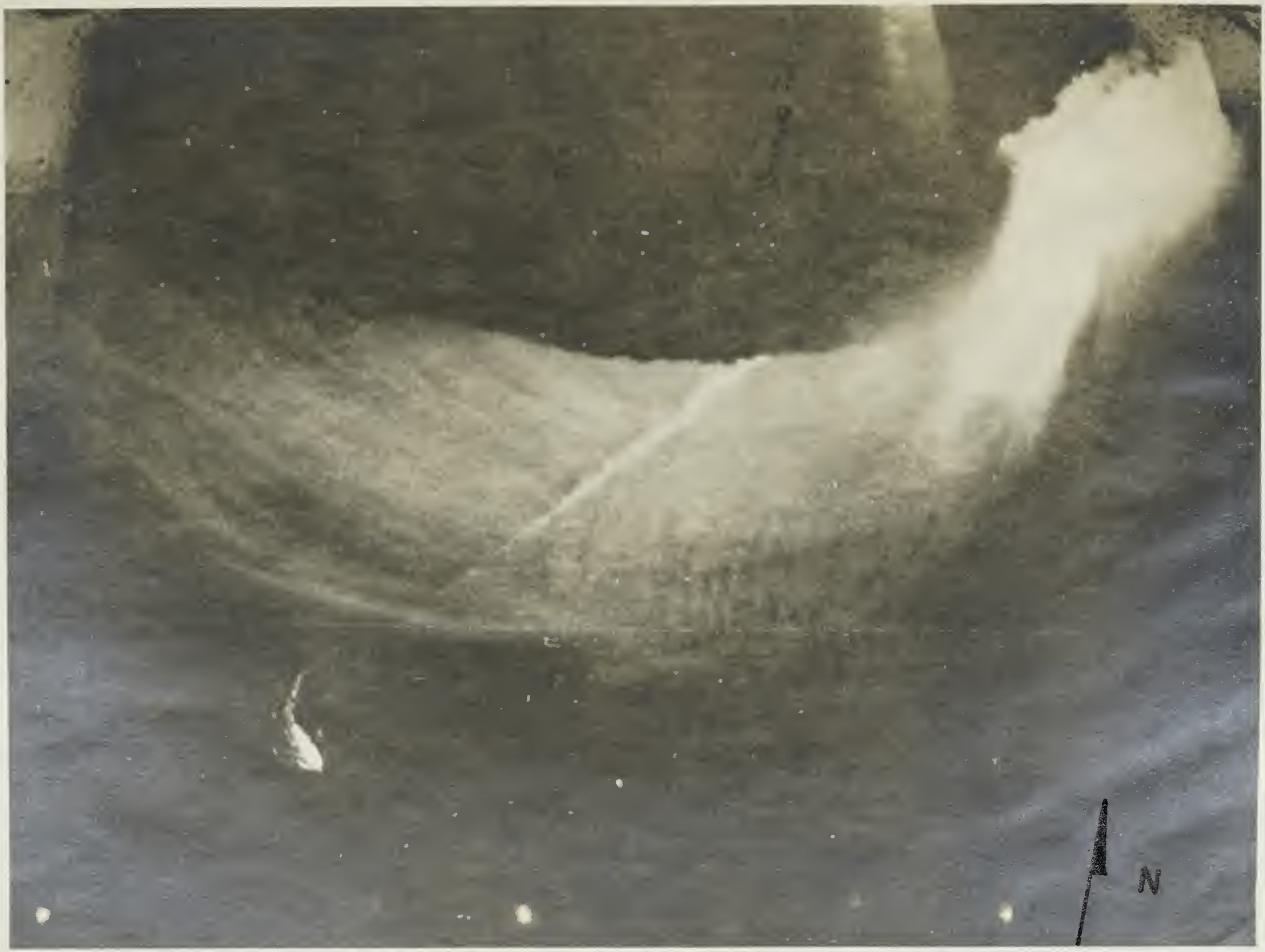


FIGURE 9

FIGURE 10.

Area B, in New York Bight,

showing movement of mass center of dye patch of October 31, 1961.

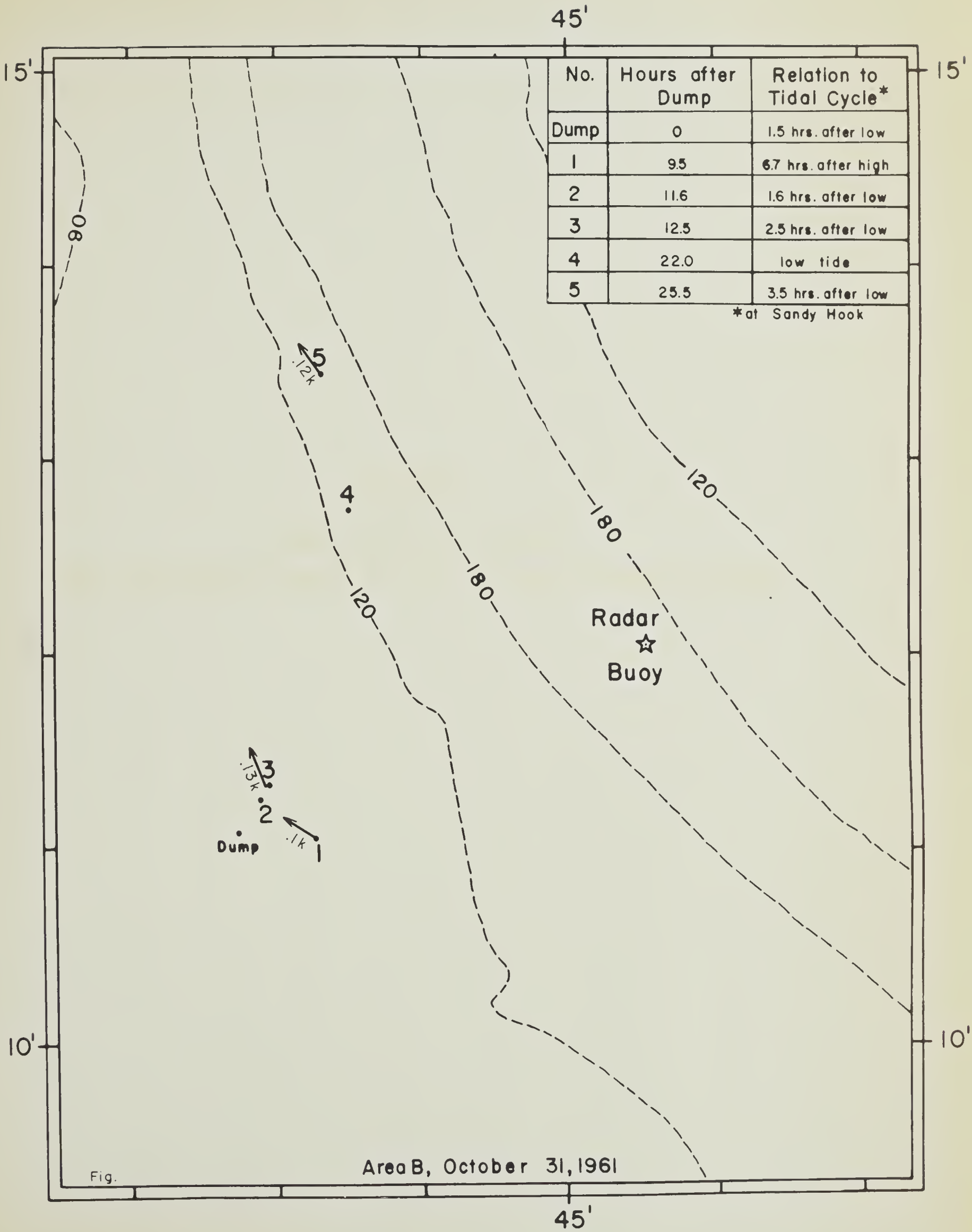
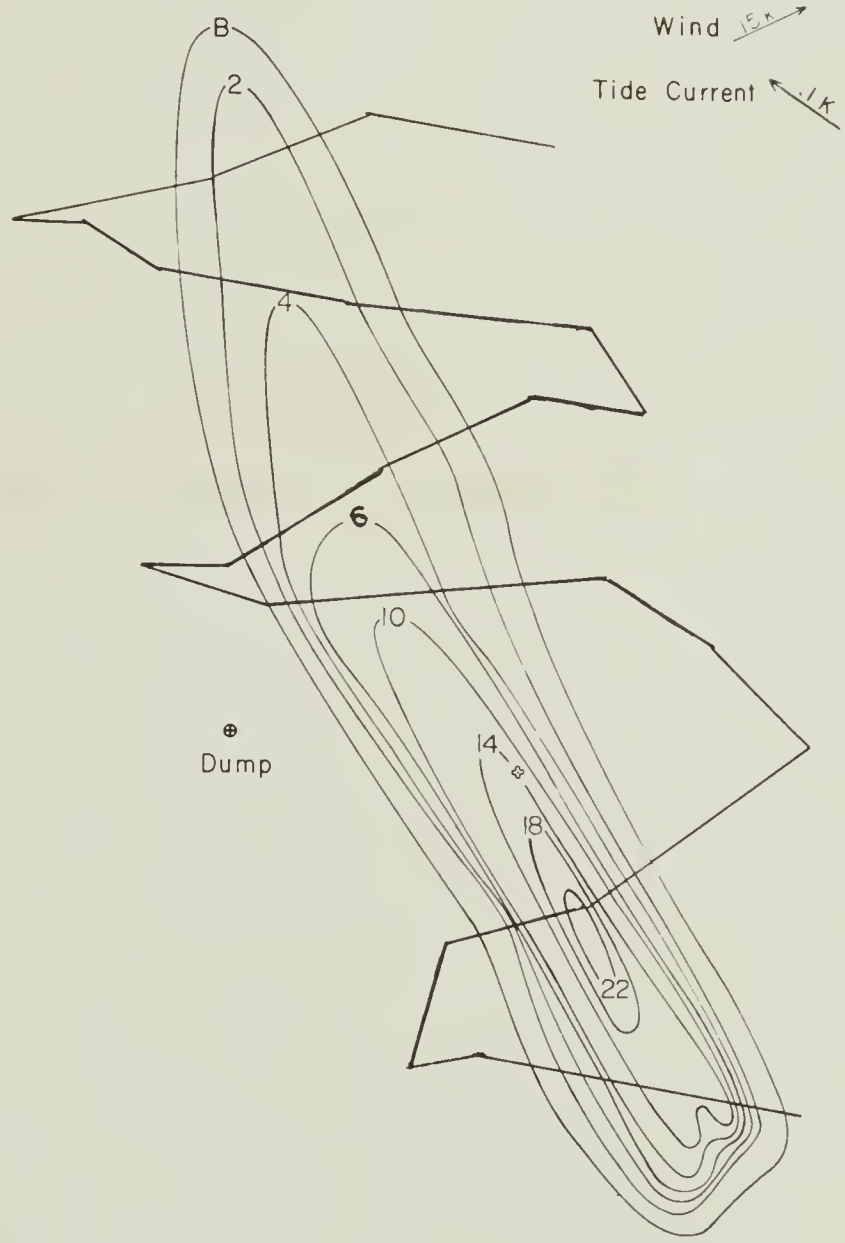

45'
15'
15'
10'
10'
45'
No.
Hours after Dump
Relation to Tidal Cycle*
Dump
0
1.5 hrs. after low
1
9.5
6.7 hrs. after high
2
11.6
1.6 hrs. after low
3
12.5
2.5 hrs. after low
4
22.0
low tide
5
25.5
3.5 hrs. after low
*at Sandy Hook
80
120
180
180
120
.12k
5
4
Radar
Buoy
.13k
3
2
Dump
.1k
1
Fig.
Area B, October 31, 1961

FIGURE 10

FIGURE 11.

Dye contour #1, October 31, 1961.



October 31, 1961
Dye Contour *1
1950 Std. Time
9.5hrs. after Dump
⊕=Mass Center
4/10 Mile

Fig.

FIGURE 11

FIGURE 11 A.

Dye contour #1, October 31, 1961

Record of one crossing shown in Figure 11.

SAMPLE OF DYE RECORD
R/V JOSEPH GOLDBERGER
OCTOBER 31, 1961

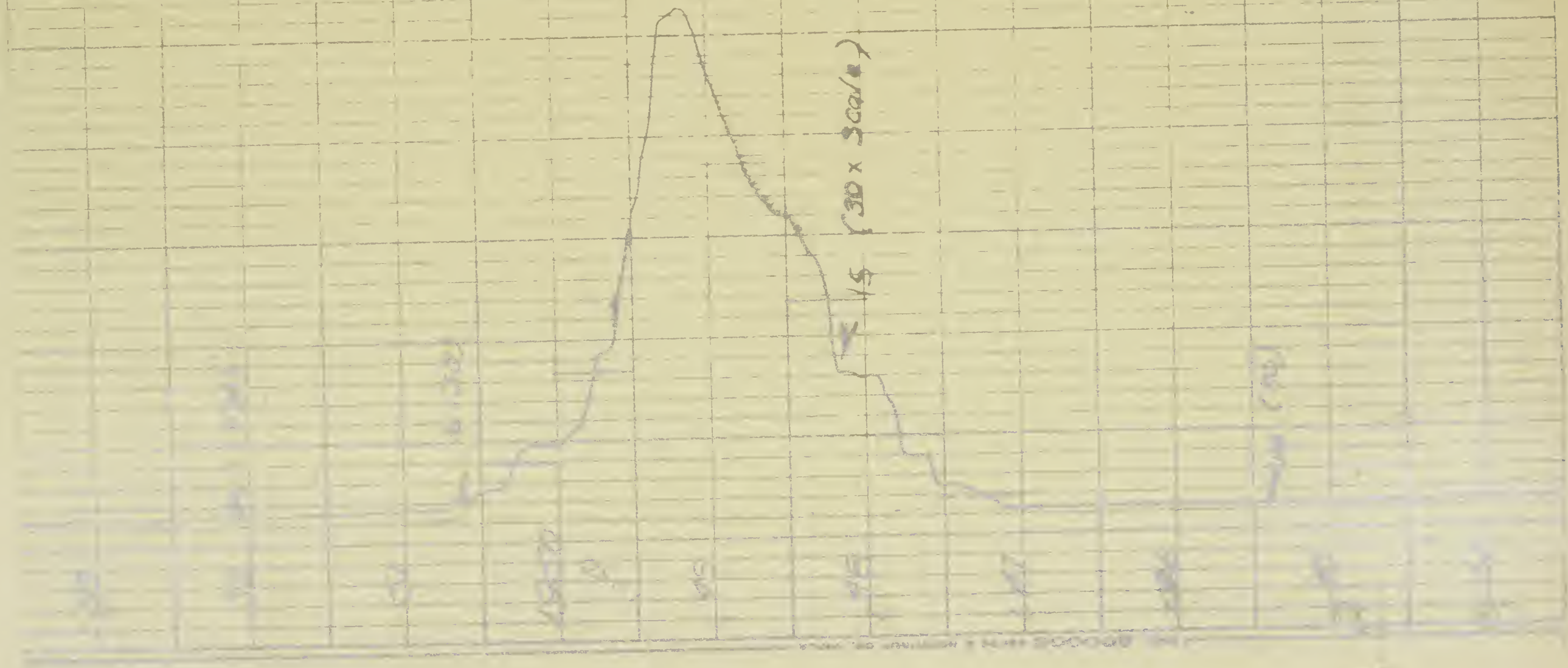
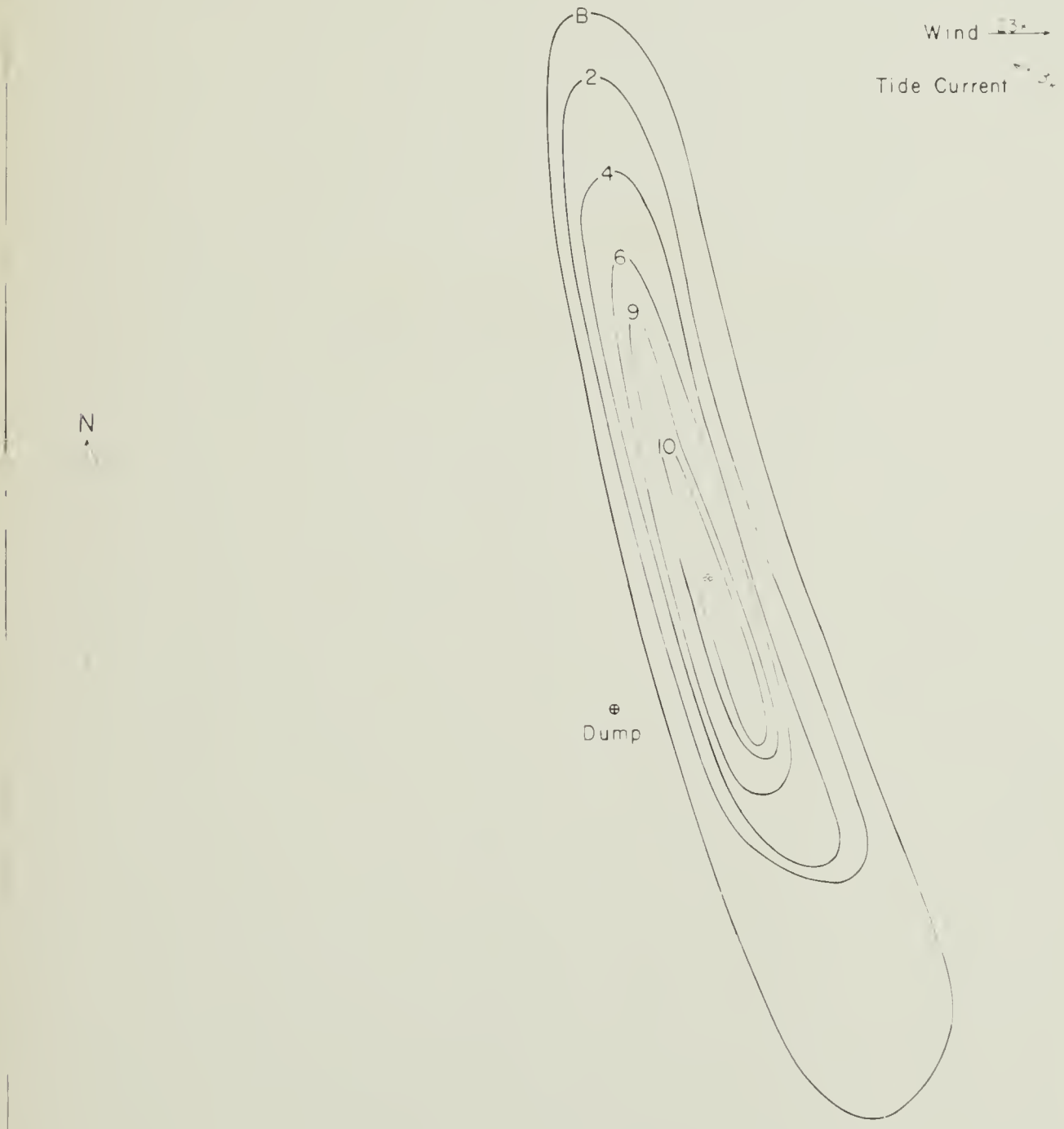


FIGURE 11 A

FIGURE 12.

Dye contour #3, October 31, 1961.



Fig

FIGURE 12

FIGURE 13.

Dye contour #5, October 31, 1961.

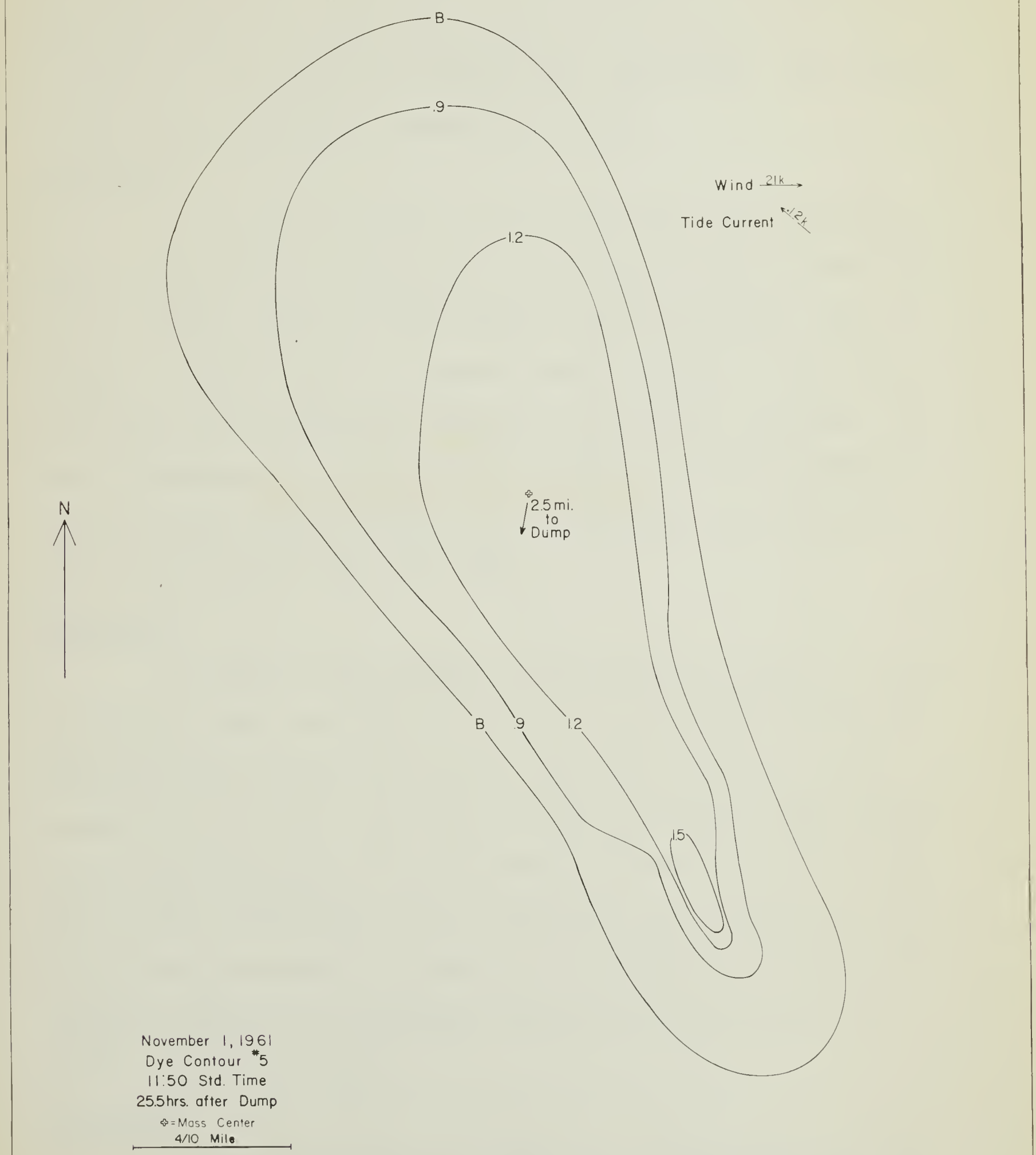


Fig.

FIGURE 13

for which contour sets were constructed, five other dye introductions were made, four of which have been roughly contoured in order to obtain information on the maximum concentration-time relationship. Some features of these experiments may be summarized as follows.

September 8

On this date one barrel of dye solution was dumped at the surface in area B. It was followed for twenty-seven hours, during which time it moved 4½ miles south southeast opposite the wind direction. This advection is believed due to the southward inshore current at this season of the year. The patch became elongated in an east-west direction. Vertical measurements of dye concentration revealed a maximum dye concentration at a depth of ten to fifteen feet and decreasing down to the level of the thermocline at about fifty feet.

October 16

One barrel of dye solution was introduced at a depth of fifteen feet at a position near Ambrose Lightship. This patch was followed for about six hours, during which time westerly winds increasing to about twenty knots prevailed. The shape of this patch remained roughly elliptical during this period. The patch moved northeasterly about 2½ miles, the velocity and direction being much the same as for the patch on October 17 already described. At this date the thermocline had all but disappeared, and vertical measurements revealed dye in decreasing concentration down to fifty feet.

October 19

A surface introduction of one barrel of dye solution was made

on this date in area B and followed for twenty-three hours. The patch moved north about 4.2 miles while light winds, shifting from south to east northeast, prevailed. The shape of this patch showed a pronounced apparent curvature to the left during the early stages (Figure 9) while the wind continued southerly.

October 30

One barrel of dye solution was introduced at the depth of fifteen feet in area B, and the developing patch was followed for about thirteen hours. During this time the patch moved 2.1 miles in a direction slightly east of north while westerly winds of ten to thirteen knots prevailed. The shape of the patch remained roughly elliptical with pronounced finger-like projections extending parallel to the crest and trough axis of the swell.

October 31

A surface dye dump of one barrel was made in area B on this date in addition to the four-barrel experiment already described. The resulting dye patch was followed for twenty-five hours, during which time it moved 4.7 miles northward. The shape of this patch was elliptical in the early period with finger-like projections aligned with the swell pattern. Later under increasing westerly winds, the shape elongated in a north-south direction.

SUMMARY OF DYE MOVEMENT:

Judging from the advection data obtained from these seven experiments in the late summer and autumn, the water movement in area A

appears to coincide with the tidal current indicated for nearby Ambrose Lightship. In area B in September the dye movement corresponded to a current of .2 knots in a south-southeast direction. In mid and late October the dye movement was to the north, indicating a current in that direction of about .2 knots velocity. These findings are in agreement with the study of Powers & Ayers indicating the circulation in this area in summer and fall is dominated by weak counterclockwise eddies close to the New Jersey shore, which carry southward the low salinity effluent of the Hudson-Raritan estuaries close to shore. Outside this coastal band about ten miles off shore in more saline water, there is a northward moving current. Superimposed on this pattern are weak tidal currents whose main vectors lie on a northwest-southeast axis, the excursion of the ebb to the southeast being of greatest magnitude. This circulation pattern is rapidly broken up in the presence of storms. The wave and swell pattern may be very complex due to reflection and refraction at the shores and refraction over the Hudson submarine Canyon.

The data from seven surface dye experiments in the New York Bight all exhibit certain features which appear to be common during the first few hours of surface dye introductions in the presence of steady, moderate winds and the absence of strong currents and high seas. These characteristics can be listed as follows:

1. The patch will initially take on a striated pattern which is aligned with the swell waves. Figures 4 and 8 show this pattern, which has the general appearance of altocumulus clouds.

2. The trailing portion of the patch which most strongly exhibits the striated pattern lies at a level below the surface. This indicates a downward mixing by the surface waves, resulting in an alignment parallel to the swell. Figure 9 illustrates this feature, where the ship, whose draft is nine feet, is stirring up dye from a subsurface depth (less than nine feet), leaving a prominent streak of dye in its wake at the surface. On the far right in this photograph, the ship's wake reveals that it has crossed the main dye patch which extends to the surface and stirred dye from the surface outward and downward.

3. Where moderate winds prevail, the dye patch takes on a distinct curvature as though the leading portion were turning to the left.

Where dye introductions have been made at a depth of fifteen feet, the early pattern retained an elliptical shape, developing finger-like projections parallel to the crests and troughs of the swell.

Table 1 summarizes the data which apply to all of these experiments.

COMPARISON OF OBSERVATIONS WITH THEORY:

In recent years several theoretical models for turbulent diffusion in the sea have been put forward. Those of Joseph and Sendner, Ozmidov, Okubo, Okubo and Pritchard, Obukov, and Schönfeld are reviewed in a recently published work by Okubo (1962). In another paper the Joseph and Sendner and the earlier Taylor theories are compared with data by Ichiye (1959). We shall not set down the various equations here, but shall only compare our data, where possible, with some of the predic-

TABLE I

	TIME	POSITION N W	AMOUNT DYE gms.	INTRO. DEPTH ft.	OCEAN DEPTH ft.	THERMO-CLINE DEPTH (BTs) ft.	WIND SPEED kts.
Sept. 8	1715	40°13.3' 73°46.1'	5.1×10^4	surf	185	50	10
Oct. 16	1155	40°26.4' 73°48.9'	3.39×10^4	15	98	none	5 to 25
Oct. 17	0930	40°27.4' 73°48.7'	3.39×10^4	surf	92	none	15
Oct. 19	1157	40°12.5' 73°44.1'	3.39×10^4	surf	120	none	10
Oct. 30	1030	40°11.1' 73°44.5'	3.61×10^4	15	121	none	10
Oct. 31	0305	40°12.6' 73°44.7'	3.61×10^4	surf	180	none	10 to 25
Oct. 31	1021	40°11.1' 73°47.3'	1.44×10^5	surf	107	none	10 to 25

DYE EXPERIMENT DATA

WIND DIRECTION	SEA STATE	TIME FOLLOWED hours	MEAN ADVECTION miles	COMPLETE CONTOUR SETS	USABLE MAX CONC.	DIFFUSION VELOCIT (CALCULATED) cm/s P(J&S)	(Taylo
S to E	2	27	4.5				
W	3	6	2.5		3		
W	2	10.1	2.8	6	4	1.0	1.3
S to E	2	23	4.2		10	1.2	
W toWSW	2	13	2.1		5	1.0	
W	2	25	4.7		6	0.49	
W to WNW	2 - 3	31	3.8	5	5	0.89	0.88

tions of these theories.

For instantaneous point-source experiments, the Joseph and Sendner, the Okubo-Pritchard, and the Schönfeld theories predict that the maximum concentration, C_{max}, will be proportional to the minus 2 power of the time; whereas the Ozmidov, Okubo, and Obukov theories predict that it will be proportional to the minus 3 power. Since nothing is known about the form of the Lagrangian correlation coefficient in the oceans, the Taylor theory is forced to consider two extreme cases:

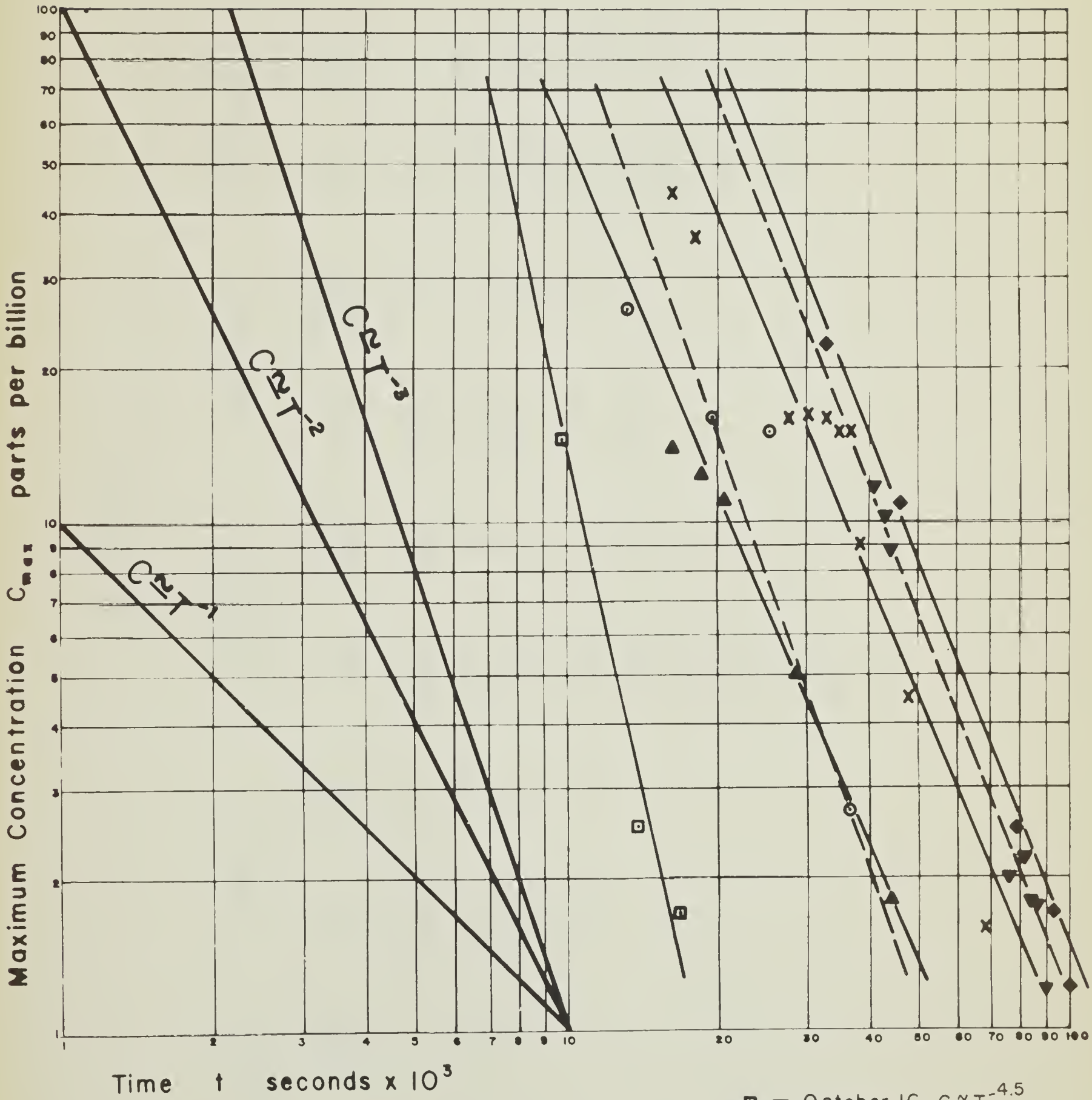
a) $T \gg L$, which predicts $C_{max} \simeq T^{-1}$

b) $T \ll L$, which predicts $C_{max} \simeq T^{-2}$

where L is the Lagrangian time scale of the turbulence and T is the time after release of the dye.

Figure 14 shows the maximum concentration, C_{max}, plotted against time for several experiments along with reference curves for $C_{max} \simeq T^{-3}$, $C_{max} \simeq T^{-2}$, and $C_{max} \simeq T^{-1}$. The data are summarized in Table II. As can be seen, most of our experiments fit, very nearly, $C_{max} \simeq T^{-2.4}$ with the exception of data from the October 16 and 17 experiments. Although this data favors neither the theories that predict $C_{max} \simeq T^{-2}$ nor those that predict $C_{max} \simeq T^{-3}$, it does seem to rule out the Taylor long-time approximation in favor of the short-time approximation, although this requires a rather large value for L. Ichiye (1959) was led to a similar conclusion from his analysis of data taken in Santa Monica Bay in experiments of much smaller scale than ours. A difficulty encountered in handling this data is that one can never be certain that the maximum concentration has in fact been observed in a

Maximum Concentration vs. Time
for several experiments



■ — October 16 $C \propto T^{-4.5}$
⊙ — October 17 $C \propto T^{-2.9}$
× — October 19 $C \propto T^{-2.4}$
▲ — October 30 $C \propto T^{-2.3}$
▼ — October 31A $C \propto T^{-2.4}$
◆ — October 31B $C \propto T^{-2.5}$

FIGURE 14

Fig.

TABLE II
(table to Figure 14)

October 16		October 17		October 19		October 30		October 31A		October 31B	
t sec	S(max) ppb	t sec	S(max) ppb	t sec	S(max) ppb	t sec	S(max) ppb	t sec	S(max) ppb	t sec	S(max) ppb
9840	14.5	13200	26	16200	44	16300	13.8	40500	11.7	32800	22.1
13920	2.5	19500	16	18000	36	18600	12.4	41600	10.4	45800	10.8
16020	1.7	25200	15	27900	16	20400	11.0	44000	8.7	78400	2.5
37200	2.7	30000	16	28400	5.0	75600	2.0	92400	1.7		
		33200	16	42000	1.8	80600	2.2	99600	1.2		
		34800	15			82100	1.8				
		36600	15			87200	1.8				
		38100	9			89400	1.2				
		47400	4.5								
		69900	1.6								

given set of crossings.

The contours reveal, in addition to the complete absence of radial symmetry, that the mass center and the point of highest concentration may be quite different. However, if an infinite number of experiments were performed in the same area, under the same conditions, and superimposed in such a way that their points of highest concentration were coincident, the expectation is that for the superimposed distribution these two points would be the same and that the contours of constant concentration would be concentric circles about this point. This expectation is based upon the assumption that those eddies which are responsible for the relative distributions are homogeneous, stationary, and isotropic. This is the situation which the several solutions treat. Since these are surface dumps and appear to be influenced by the wind and swell to varying degrees, this is not strictly true, and indeed it probably is not true in nature in any case. Furthermore, our data are obtained from single experiments, not an infinite number of superimposed experiments. Nevertheless, to enable some comparison with the proposed solutions, we assume that for each experiment we can use, in place of the radii of concentric circles, equivalent radii, $\bar{r}_i = \sqrt{\frac{A_i}{\pi}}$, where A_i is the area enclosed by the ith contour.

Figures 15 and 16 show log C vs. equivalent radius for the two experiments which yielded sufficient data. Even with the fairly large uncertainties in $\bar{r}_i$ (estimated at about 10% for the October 17th experiment and 8% for the October 31st experiment), most of our data do not fit a linear relationship as predicted by the Joseph and Sendner

Concentration vs. Equiv. Radius
October 31, 1961

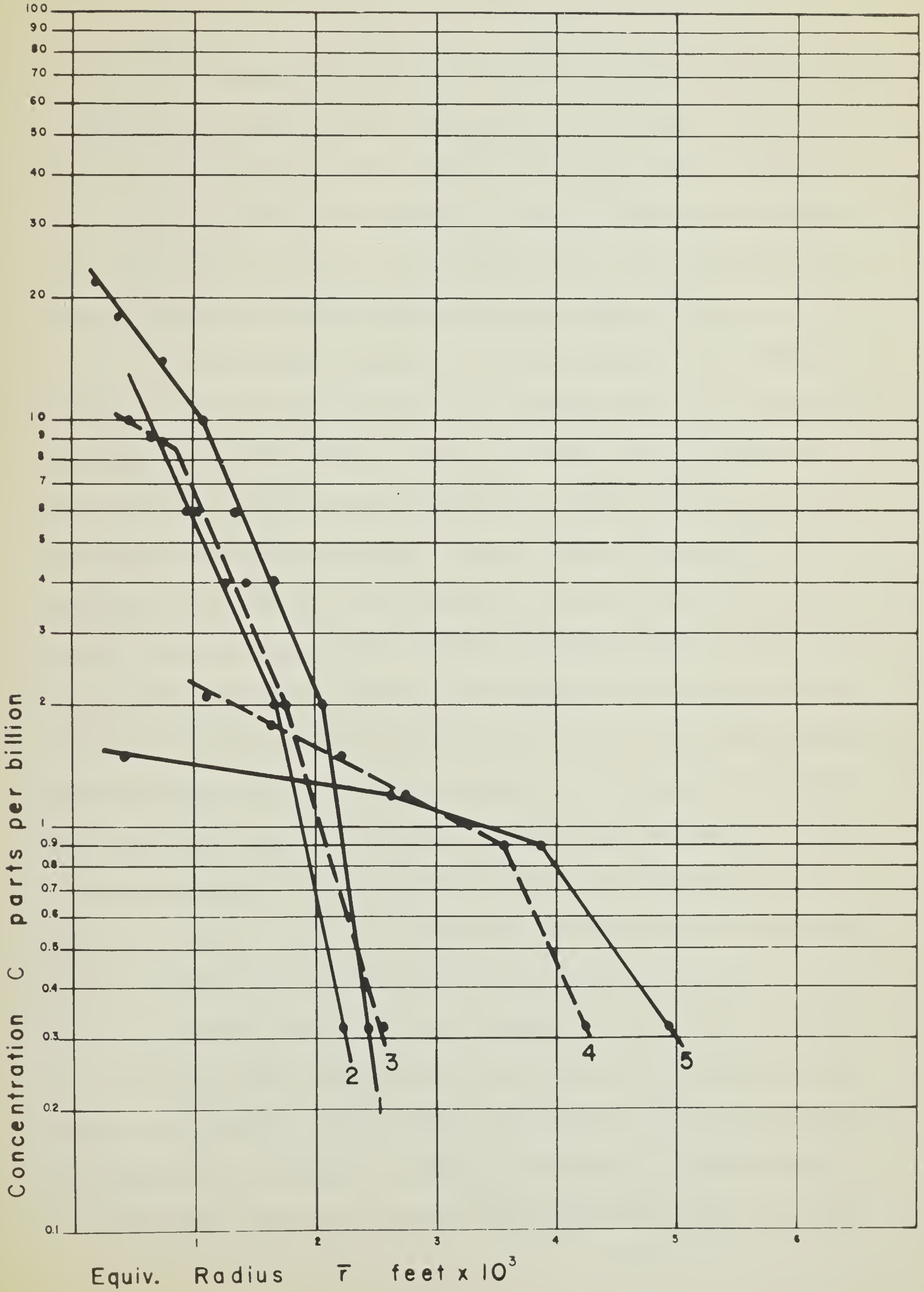


FIGURE 16

Fig.

theory. The curves are drawn not smooth so as to illustrate this and to enable easier comparison with Figures 17 and 18, which are plots of log C vs. $\bar{r}^2$ for the same data (Tables III & IV). As can readily be seen, a linear relationship between log C and $\bar{r}^2$ fits our data quite well. This would correspond to the predictions of the Okubo-Pritchard theory, the Obukov theory, and also the older Taylor theory.

The fluorometers measure the concentration, C, in terms of the amount of dye per unit volume of the sampled water. The respective solutions discuss the amount of dye, S, per unit area of dye patch. Since extensive vertical measurements were not made, it was necessary to estimate the depth of the dye. In most cases this was done from knowledge of the amount of dye inserted, the areas between the closed contour lines, and by assuming that the concentration at any point was nearly uniform from the surface to the bottom of the dye cloud. The verticals that were taken reveal that this is only a fair approximation. Multiplying C_{max} by this depth, d, gives S_{max}, the amount of dye per unit area at the high concentration "center", and enables calculation of the characteristic parameters of the various solutions from the S_{max} vs. t curves. For P, the "diffusion velocity" of the Joseph and Sendner solution, the data from five of our experiments yield a mean value of 0.9 cm/sec with an average deviation of 0.16 cm/sec or about 17%. For non-oceanic experiments in the vicinity of Chesapeake Bay, Pritchard and Carpenter (1960) found 0.32 cm/sec in the Holland Straits, 0.2 cm/sec in the Conowingo Reservoir, 0.5 cm/sec in an unspecified location, while Joseph and Sendner (1958) have found between 0.8 and

Concentration vs. Area/π
October 17, 1961

Concentration C parts per billion

Equiv. Radius Squared $\bar{r}^2$ feet^2 x 10^3

1
2
3 15'
4
5
6
Data

FIGURE 17

Fig.

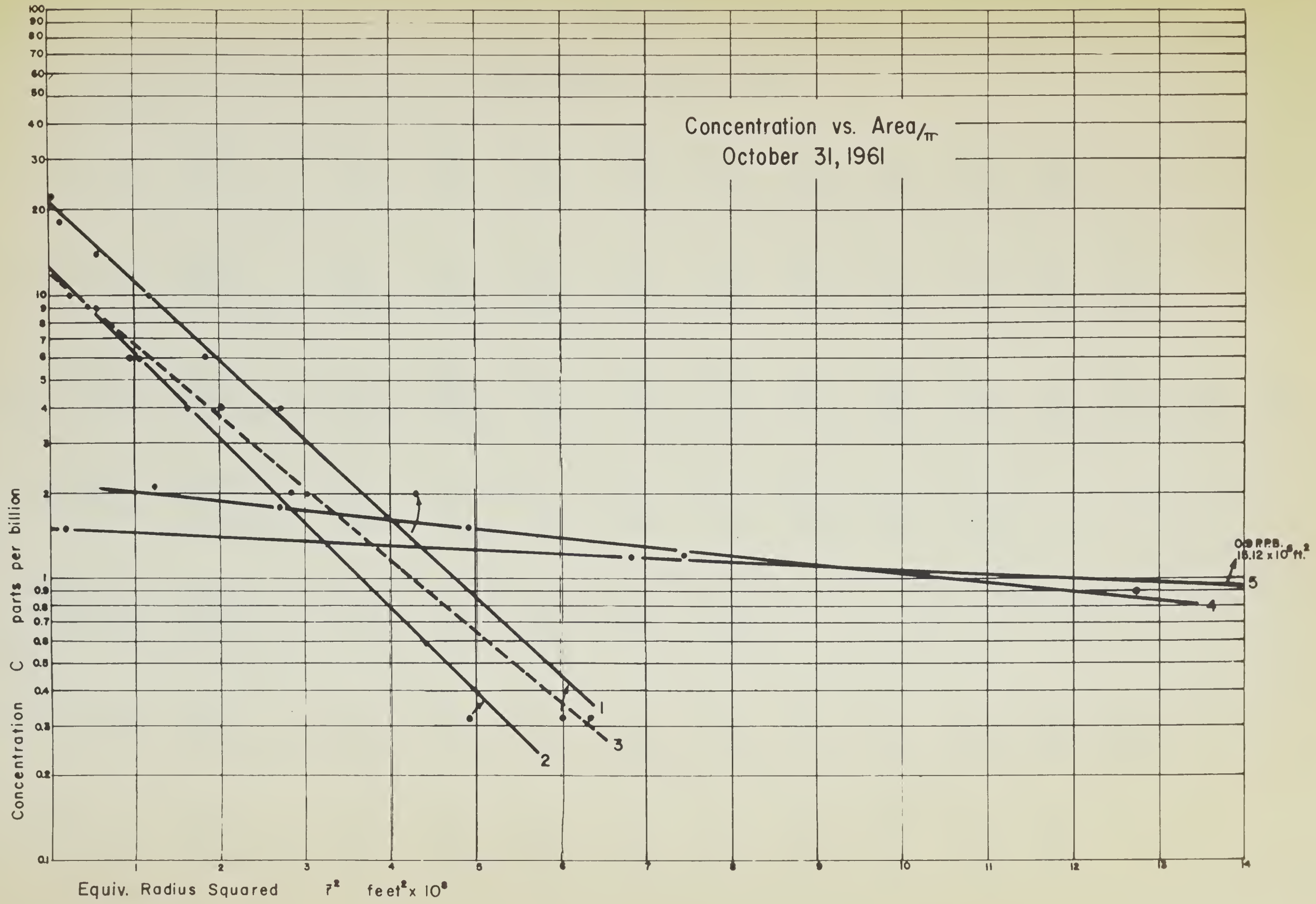


Fig.

FIGURE 18

TABIE III
(table to Figures 15 and 17)

Experiment of Oct. 17, 1961

I	S(ppb)	29	18	16	12	10	8	6	4	2			
t = 7,000 sec	r(ft)	293	330	604	654	774	878	917	1017	1170			
	$r^2x10^6(ft^2)$	0.858	1.09	3.65	4.28	5.99	7.71	8.41	10.3	13.7			
II	S(ppb)	19	16	15	13	11	10	8	6	4	2		
t = 11,700sec	r(ft)	158	210	434	557	680	785	932	1170	1250	1391		
	$r^2x10^6(ft^2)$	0.250	0.441	1.88	3.10	4.62	6.16	8.69	13.7	15.6	19.4		
IIIsfc	S(ppb)	26	24	22	21	19	15	13	11	9	7	5	3
t = 13,300sec	r(ft)	66	115	222	285	395	438	485	564	654	710	771	827
	$r^2x10^6(ft^2)$	0.0436	0.132	0.493	0.812	1.56	1.92	2.35	3.18	4.28	5.04	5.94	6.84
III 15'	S(ppb)	13	10	9	8	7	4	3	2				
t = 14,700sec	r(ft)	149	237	381	539	644	741	836	962				
	$r^2x10^6(ft^2)$	0.222	0.562	1.45	2.91	4.15	5.49	6.99	9.25				
IV	S(ppb)	15	12	9	6	3							
t = 19,600sec	f(ft)	219	459	707	879	1120							
	$r^2x10^6(ft^2)$	0.480	2.11	5.00	7.73	12.5							
V	S(ppb)	15	11	10	9	8	7	5	3	2	1		
t = 26,200sec	r(ft)	145	282	399	495	558	606	816	1020	1260	1500		
	$r^2x10^6(ft^2)$	0.210	0.795	1.59	2.45	3.11	3.67	6.66	10.4	15.8	22.6		
VI	S(ppb)	2.7	2.3	1.9	1.7	1.3	1.0	0.5	0.3	0.1			
t = 36,400sec	r(ft)	105	202	281	345	396	453	507	549	705			
	$r^2x10^6(ft^2)$	0.110	0.408	0.790	1.19	1.57	2.05	2.57	3.01	4.97			

TABLE IV
(table to Figures 16 and 18)

Experiment B. Oct. 31, 1961

I	S(ppb)	22	18	14	10	6	4	2	0.32
t = 33,800 sec	r(ft)	201	384	750	1092	1356	1656	2076	2454
	$r^2x10^6(ft^2)$	0.0404	0.147	0.563	1.192	1.839	2.742	4.310	6.022
II	S(ppb)	9	6	4	2	0.32			
t = 41,300 sec	r(ft)	684	996	1272	1686	2214			
	$r^2x10^6(ft^2)$	0.468	0.992	1.618	2.843	4.902			
III	S(ppb)	10	9	6	4	2	0.32		
t = 44,500 sec	r(ft)	488	738	1044	1428	1734	2520		
	$r^2x10^6(ft^2)$	0.238	0.545	1.090	2.039	3.007	6.350		
IV	S(ppb)	2.1	1.8	1.5	1.2	0.9	0.32		
t = 79,000 sec	f(ft)	1104	1650	2214	2730	3570	4248		
	$r^2x10^6(ft^2)$	1.219	2.723	4.902	7.453	12.76	18.05		
V	S(ppb)	1.5	1.2	0.9	0.32				
t = 91,300 sec	r(ft)	415	2610	3888	4950				
	$r^2x10^6(ft^2)$	0.175	6.812	1512	24.50				

1.5 cm/sec for open ocean phenomena.

From the slopes of the curves in Figures 17 and 18 we can calculate $\sqrt{\overline{v}^2}$, the turbulent velocity of the Taylor theory. For this the October 17 experiment gives a mean $\sqrt{\overline{v}^2}$ of 1.3 cm/sec, and the October 31-B experiment gives 0.88 cm/sec. In both cases the average deviation is almost 50%; however, in both cases the data suggest that $\sqrt{\overline{v}^2}$ may have varied systematically with time. It remains to be seen if further experiments bear this out and, if so, what significance can be attached thereto. Ichiye, in analyzing data taken in Santa Monica Bay, was led to values of 0.6 and 0.7 cm/sec for $\sqrt{\overline{v}^2}$.

In the time since these experiments were performed, our techniques have been improved, and the newer, more reliable data now being processed should permit a more extensive analysis. Therefore, the results of this study should be considered to be of a preliminary nature.

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